

Studies of Gas-Phase Condensation of Jet A Vapor in Fuel Tank Ullage: Summary of Progress and Plans

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Background:

- Clouds, presumably comprised of light hydrocarbons from jet fuel, have been observed in center wing fuel tanks of large commercial aircraft during routine maintenance.
- The presence of suspended fuel droplets can significantly lower the lean flammability limit.
- The application of equilibrium-based flammability envelopes to the dynamic environment of aircraft fuel systems can lead to serious errors in the assessment of the risk of explosion/fire.
- Two distinct dynamic conditions occurring in aircraft fuel systems can result in the formation of fuel mists:
 1. Sloshing and vibration (agitation)
 2. Pressure changes (homogeneous gas-phase condensation).

Prior Work:

- Nester (1967) and Ott (1970) investigated the flammability of Jet A *mists and sprays created by mechanical agitation* of small amounts of fuel and reported that the lean flammability limit temperatures could be lowered by as much as 60 F.
- No attempt was made to characterize the mists/sprays even though these investigations acknowledged that droplet number density and droplet size distribution were important parameters in assessing the flammability limits of fuel vapor- droplet- air mixtures.
- No attempt was made to investigate the formation of aerosols by homogeneous gas-phase condensation even though such phenomena were acknowledged as relevant and important.
- In consideration of these studies, one can only conclude that little is known about either the stability of aerosols formed in aircraft fuel systems. or the resulting changes to the flammability envelope.

Present Study:

Preliminary Results:

- A fuel tank test facility comprised of a large temperature-, pressure- regulated fuel tank segment with optical access for PDPA measurement of droplet size distribution and density has been built to investigate the formation of Jet A fuel clouds by homogeneous gas-phase condensation.
- Preliminary facility testing resulted in the formation of a clearly visible fuel cloud at atmospheric pressure (argon) with tank top at 55 F and tank bottom at 90 F.
- Testing during PDPA equipment demonstrations (prior to purchase) allowed preliminary quantitative measurements of droplet formation at the conditions reported above over a 40 minute interval.
 1. Droplet growth from 1 to 15 microns was observed
 2. An increase in observable particle density up to $2 \times 10^9/\text{in}^{-3}$ was measured
 3. Degradation of optical properties due to surface condensation was noted.
 4. In subsequent experiments homogeneous gas phase condensation diminished

- No additional testing has been conducted while waiting for the PDPA equipment arrival, installation and training.

Lessons Learned from Preliminary Testing, Subsequent and Current Activities:

- Video recordings of the diffuse cloud that formed in the test cell with normal lighting proved to be somewhat unsatisfactory. At the Third Triennial International Fire & Cabin Safety Research Conference held in Atlantic City, NJ in October 2001, it was suggested that some attention be devoted to obtaining good quality video documentation of the process. As a result, a high-power line-laser illumination system has been assembled and added to the test facility.
- Several possible explanations for the reduction in cloud density over a series of preliminary tests were developed in meetings between WSU and Boeing researchers. It was suggested that this phenomenon could be the result of: a) changing fuel composition caused by using the same fuel in sequence of experiments, b) competition between homogeneous, gas-phase condensation and heterogeneous surface condensation developed as a result of tank surface seasoning, c) some slight variation in experimental conditions.
- In order to minimize the influence of the run-to-run variation in fuel composition, several new protocols were developed: a) fresh fuel must be used for each new experiment, b) each batch of fuel must be analyzed before and after an experiment to determine flash point, c) GCMS chemical analyses of fuel before and after an experiment will be occasionally obtained, and d) chemical analyses of vapor and condensate are important and some method of sample collection needs to be devised.
- Several approaches to understand the scope and mechanism of competition between homogeneous, gas-phase condensation and heterogeneous surface condensation were developed. First, the tank surfaces were washed in order to determine if the wall seasoning theory had merit. Vigorous cloud formation was noted in an experiment performed after the walls were washed, thus lending credence to the theory. Second, the tank surfaces were treated with the cadmium-based coating used in aircraft fuel tanks to assure that future experimental results will be representative of aircraft fuel tank conditions. Third, it was decided that an experimental protocol to match ground/flight ops needs to be developed in order to quantify the influence of wall seasoning on the competition between homogeneous, gas-phase condensation and heterogeneous surface condensation.
- Modifications to the test cell were made in order to compensate for the degradation of optical properties of windows due to surface condensation. The windows were replaced with a glass coated polycarbonate in order to decrease clouding/scratching. A wiper system was designed and installed.
- Problems with overheating of the test cell vacuum pumping system arose during preliminary facility testing. The system uses a high flow rate water recirculation system to pull a vacuum on the test cell via a water jet ejection nozzle. The water heats up to >150 F within an hour of continuous operation. Since the minimum test cell pressure is limited by the saturation pressure of the water jet in the nozzle, a cooling system had to be devised. A heat exchanger has been built and is being installed in the recirculation system.
- FAA Tech Center project monitors, the FAA National Resource Specialist on Fuel Tank Safety, and the Principle Investigators from WSU/Boeing-Wichita, met in February to coordinate the research with other related fuel tank safety activities and to discuss future directions. Several substantive issues arose: a) the FAA National Resource Specialist

expressed his view that the results of the research was very important to further development of an accurate explosion risk analysis model, b) work at NJIT on the fuel tank condensation modeling was relevant and coordination between the WSU/Boeing and NJIT work is essential, c) fuel tank thermal modeling results from Boeing were discussed and it became apparent that the addition of independent temperature control of four walls on the test cell was necessary (the original design only allows for two).

- The Dantec PDPA equipment was purchased and set up in March 2002. An input channel necessary for droplet sizing measurements failed during the manufactures installation and training visit. The equipment was sent to Denmark for repairs and the manufacture is scheduled to setup the equipment and train WSU personnel June 26-27.

Future Activities:

- The previously discussed influence of wall seasoning on the competition between homogeneous, gas-phase condensation and heterogeneous surface condensation will be addressed in near-term experimental activities. A series of experiments will be conducted to qualify the anticipated reduction in cloud formation as tank walls become "seasoned" over the course of repeated exposure to fuel vapor. Test conditions will be the same the preliminary experiments. Temperature, pressure and droplet size measurements will be obtained along with video imaging of the experiments. Results will be analyzed to determine fuel vapor/droplet mass, and hence, equivalence ratio (flammability limits).
- These results, together with Boeing data on typical CWT fuel loading history and thermal modeling will be used to guide the development of a protocol to conduct further experiments.
- WSU/Boeing researchers will meet with FAA Tech Center/NJIT researchers in July or August to exchange data and coordinate activities.
- Remaining FAA capital equipment money will be used to purchase digital imaging equipment.
- Remaining WSU capital equipment money will be used to purchase two additional heater/chiller units to allow experimental investigation guided by Boeing fuel tank thermal modeling.
- Additional FAA funding for a cost extension to the current contract is currently being sought in order to support research activities through until 2003.
- FAA sponsored work will be directed toward mapping conditions where fuel cloud formation is significant. Results will include estimation of dynamic flammability limits.
- Two reports will be written for presentation at the WSU/Boeing/FAA meeting in October 2002. One paper will discuss experimental results and the other will discuss fuel tank thermal modeling.